Progress In Tin Ion Spectroscopy

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EUV Plasma Processes


Joris Scheers


Francesco Torretti


Ruben Schupp


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Alex Bayerle


Mart Johan Deuzeman


Wim Ubachs


Oscar Versolato

ARCNL

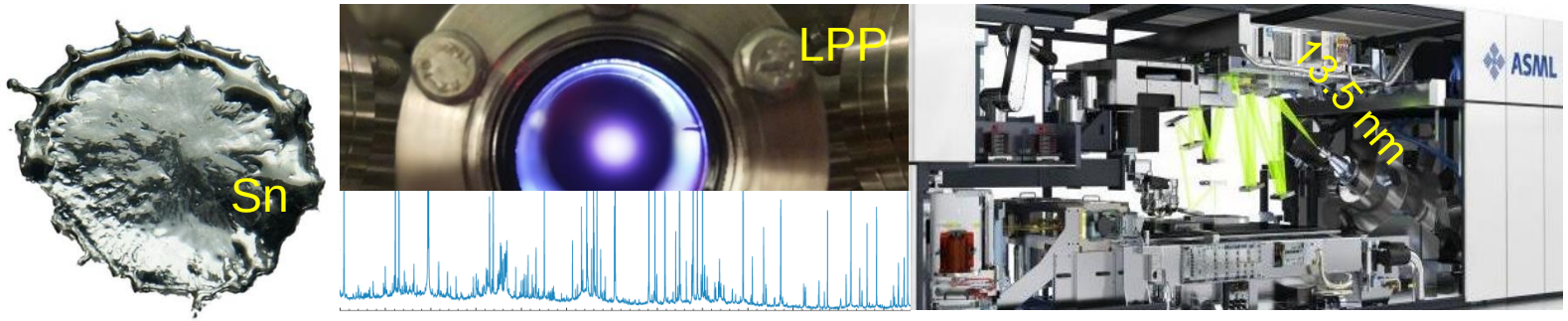
ADVANCED RESEARCH CENTER FOR NANOLITHOGRAPHY

FOM NWO FOM Institute AMOLF | Universiteit van Amsterdam | VU Vrije Universiteit Amsterdam | Gemeente Amsterdam | Provincie Noord-Holland | ASML

outline

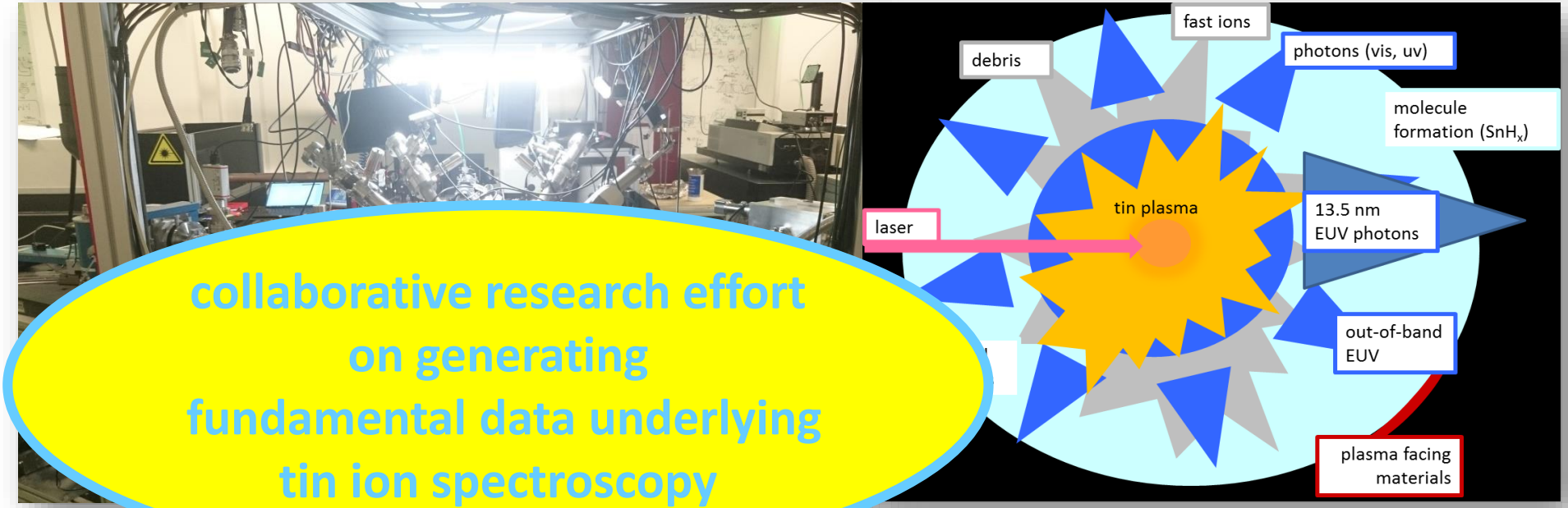
advanced research center for nanolithography

EUV sources (talk: Oscar Versolato) and nanolithography related research



- Tin spectroscopy on and around the ARCNL
  - EBIT-based optical spectroscopy (Sn ions: 7+ - 15+)
  - LPP-based out of band EUV spectroscopy (Sn ions: 7+ - 15+)
  - LPP-based optical spectroscopy on lowly charged tin ions
- Conclusion/outlook

The LPP at ARCNL



collaborative research effort on generating fundamental data underlying tin ion spectroscopy

laser produced plasma is an extremely complex system / problem

light = monitoring, diagnostics tool → spectroscopy

spectroscopy = diagnostics requires:

- line identification, energies levels,
- population dynamics (ionization, excitation, DR and RR recombination, CX, energy distributions, …… per ionic species)

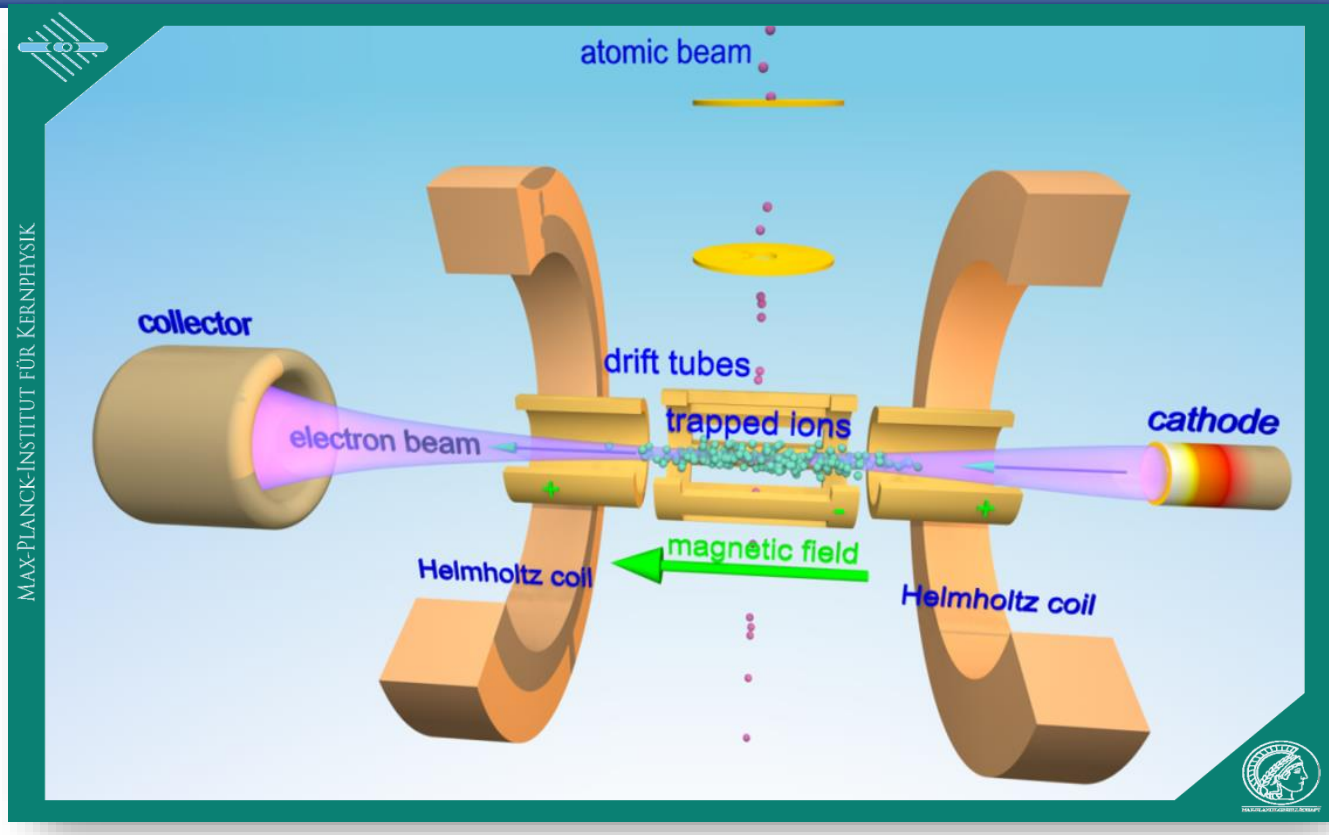
el. conf. Sn
$[Kr]4d^{10}5s^25p^2$
q+<15+
open d shell

In-EBIT spectroscopic fingerprint data

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

EBIT group:
J. Crespo López-Urrutia
H. Bekker
S. Dobrodey
A. Windberger

electron impact excitation of trapped Sn ions in charge states 7 - 15+



Theory

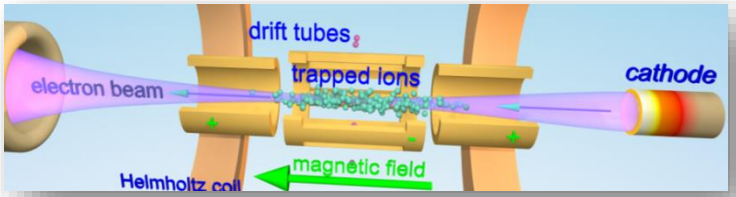
ISAN Troitsk
A. Ryabtsev

School of Chemistry
E. Eliav and U. Kaldor

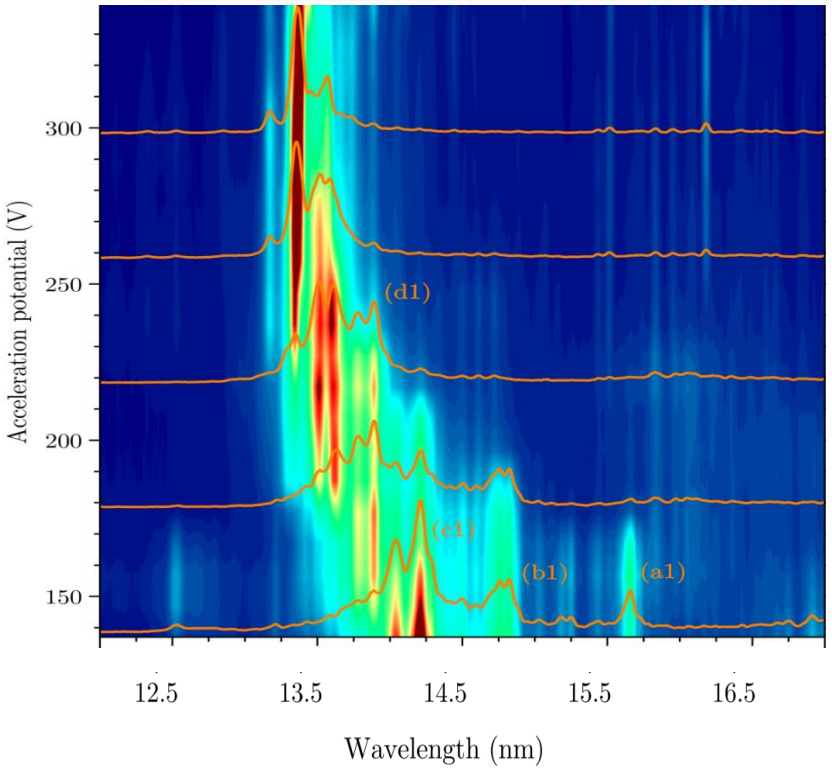
Van Swinderen Institute
A. Borschevsky

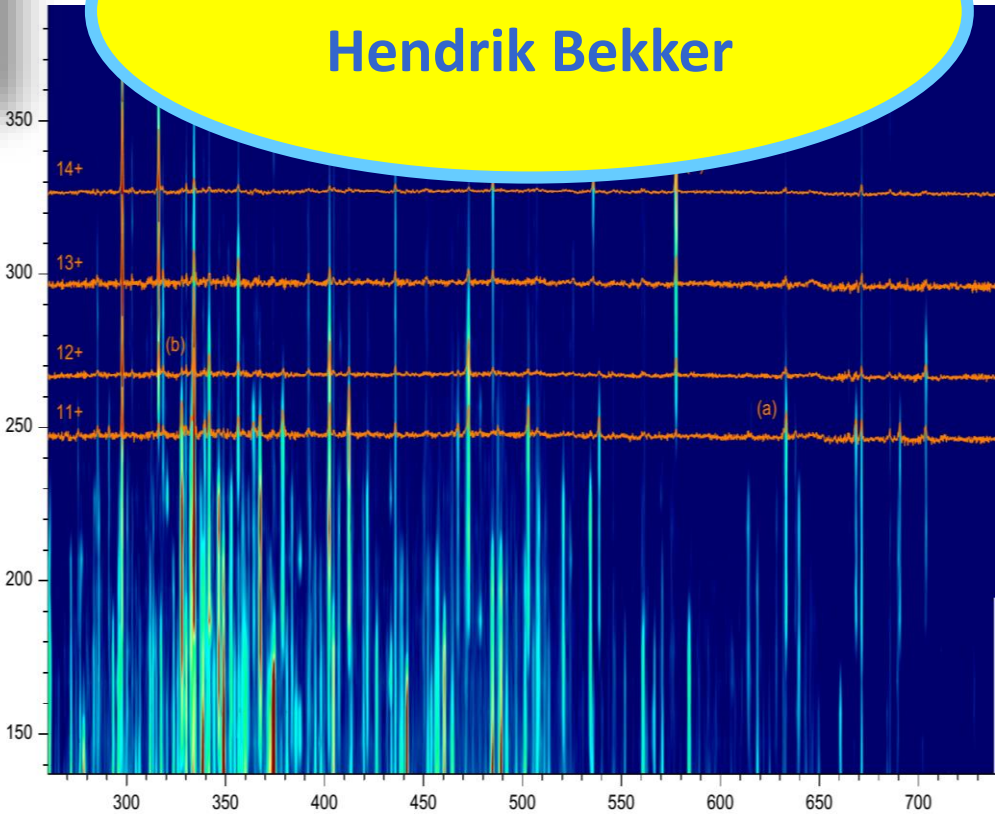
School of Physics
J. Berengut and E. Kahl

Sn^{7-14+} In-EBIT spectroscopy



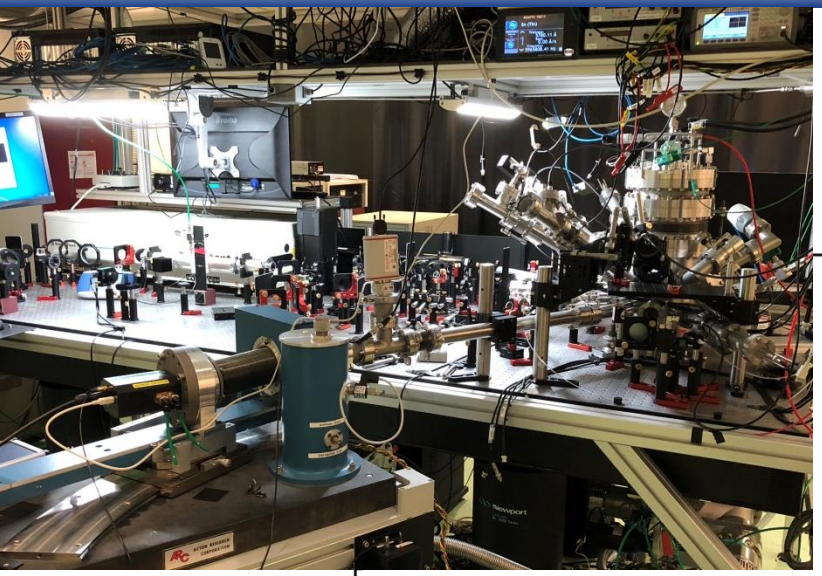
Talk
Hendrik Bekker



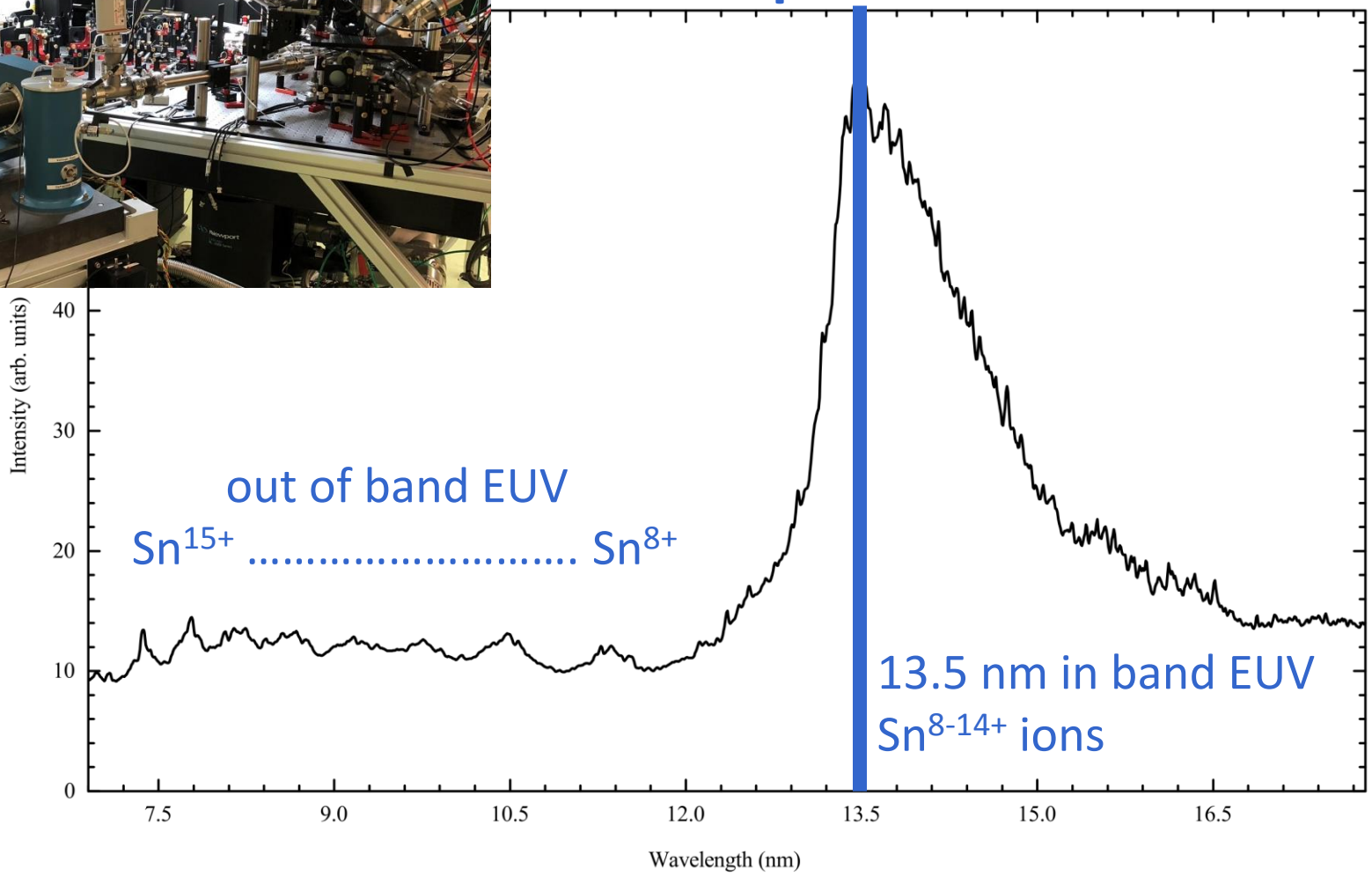


Windberger *et al.*, Phys. Rev. A **94**, 012506 (2016)
Torretti *et al.*, Phys. Rev. A **95**, 042503 (2017)

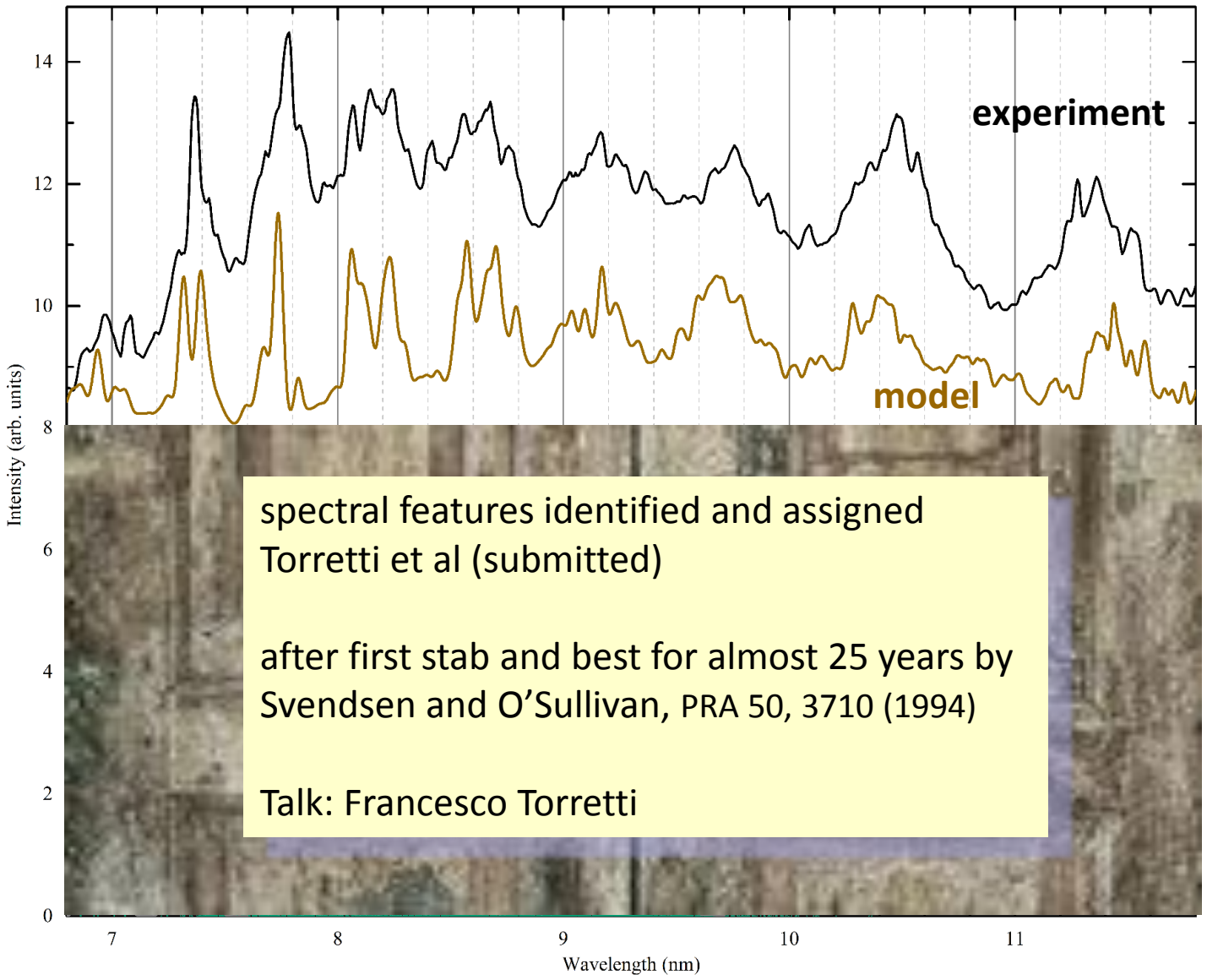
out and in band EUV emission



LPP EUV spectrum



LPP out of band spectrum



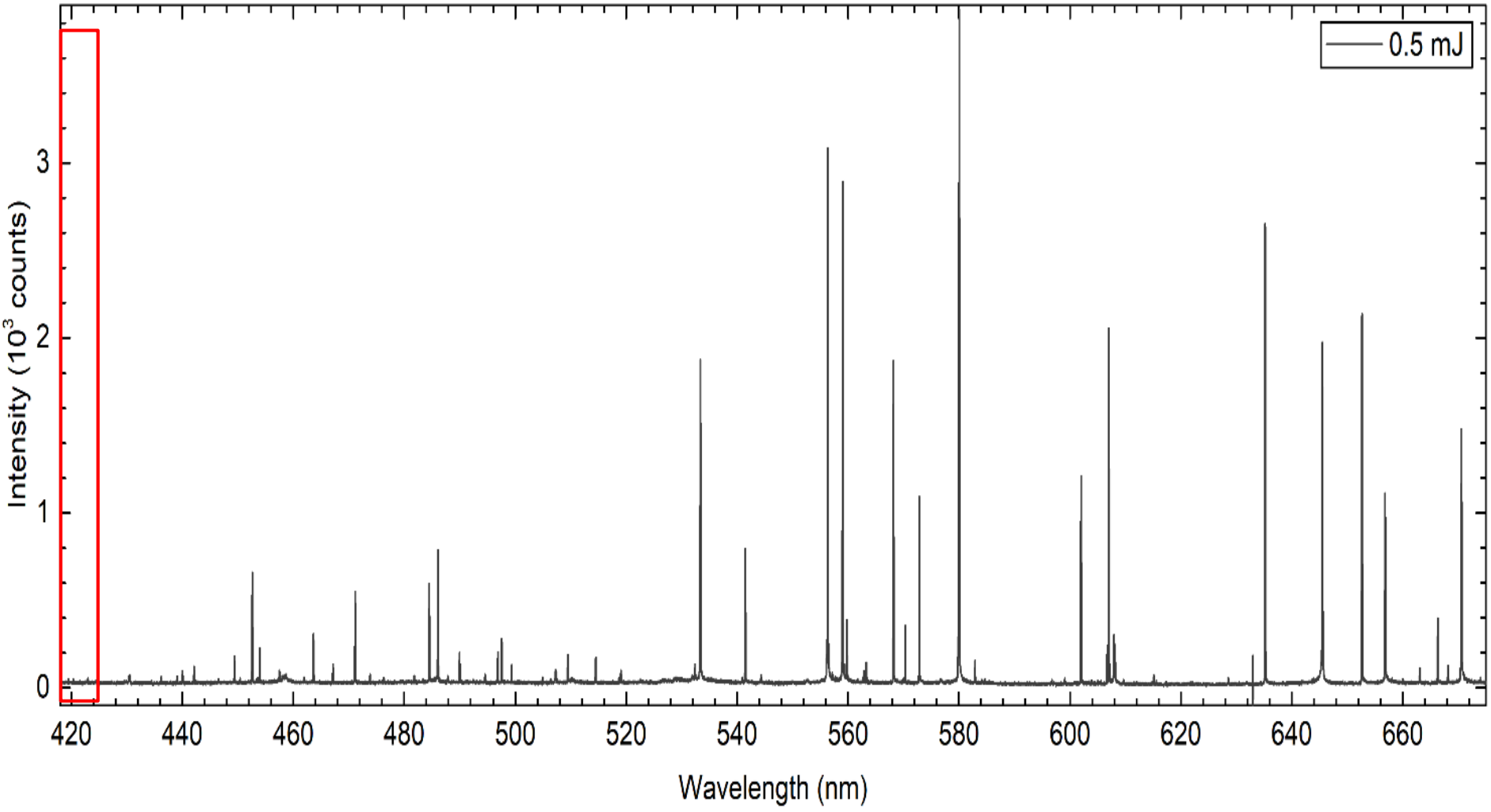
spectral features identified and assigned Torretti et al (submitted)

after first stab and best for almost 25 years by Svendsen and O'Sullivan, PRA 50, 3710 (1994)

Talk: Francesco Torretti

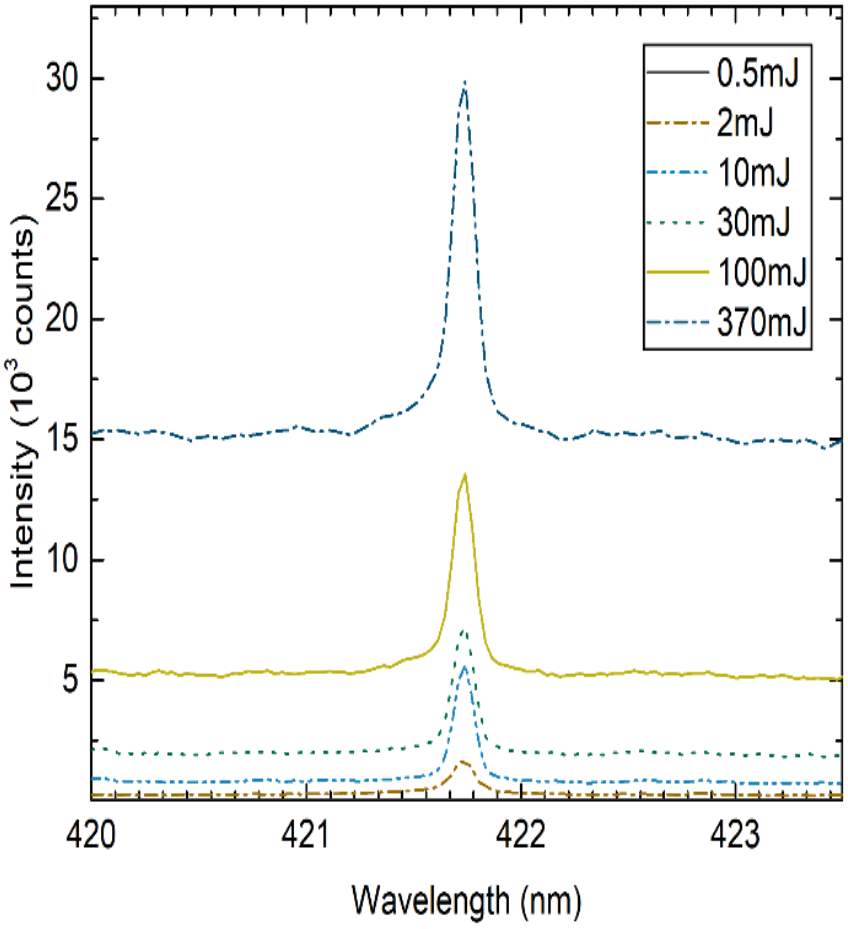
optical spectra of low charge state Sn

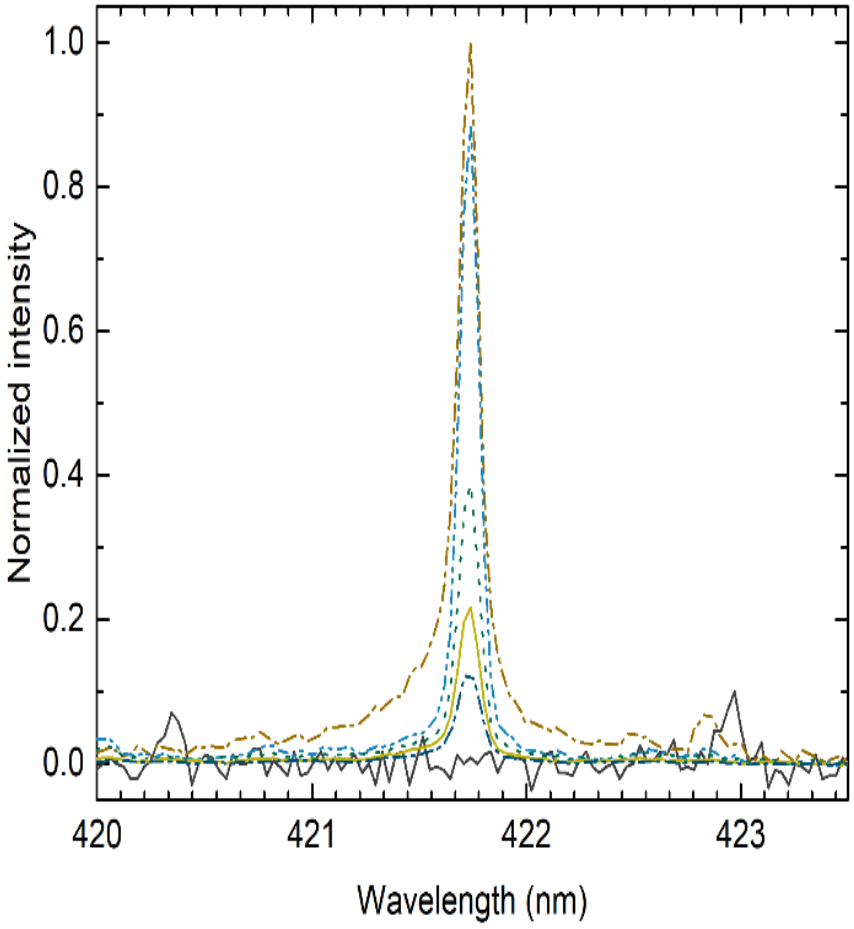
Joris
Scheers



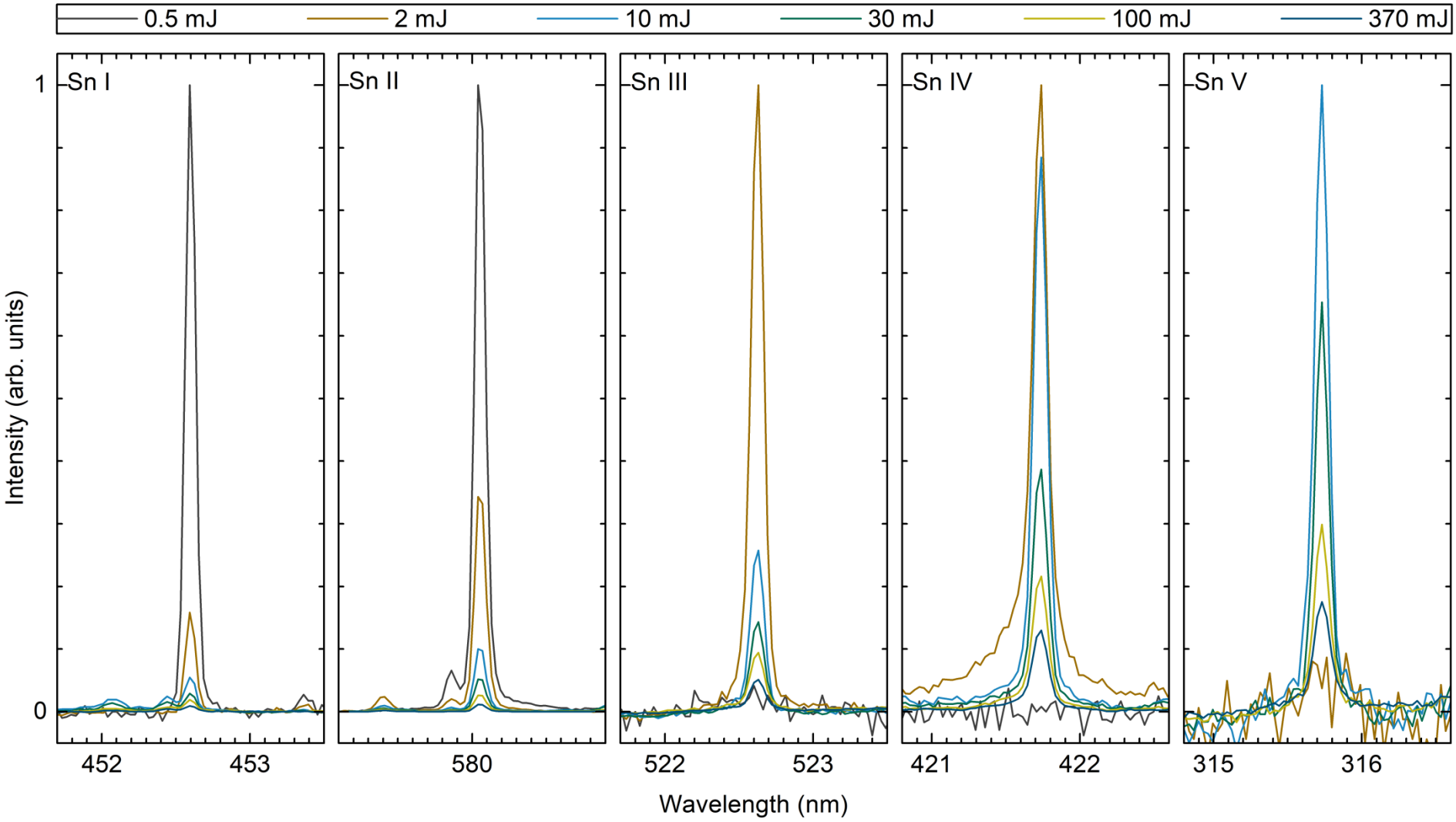
intensity of the spectrum

$6s\ ^2S_{1/2} - 6p\ ^2P_{1/2}$



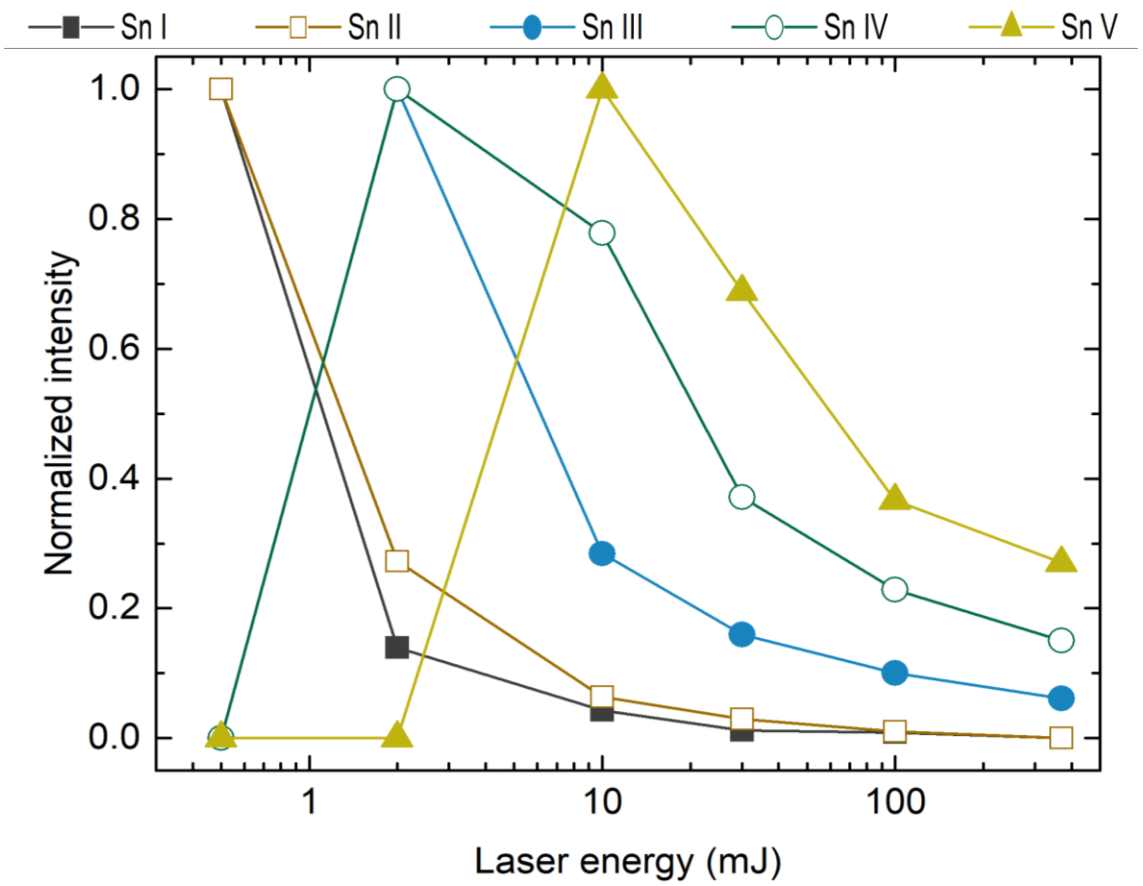


line intensities



$5p^2\ {}^1S_0 - 5p6s\ {}^1P_1$ $5d\ {}^2D_{5/2} - 4f\ {}^2F_{7/2}$ $6s\ {}^1S_0 - 6p\ {}^1P_1$ $6s\ {}^2S_{1/2} - 6p\ {}^2P_{1/2}$ $6s\ {}^3D_3 - 6p\ {}^3F_4$

normalization to continuum



# lines	
SnI	35
SnII	39
SnIII	76
SnIV	47
SnV	86

Sn IV

# lines	
SnIV	47

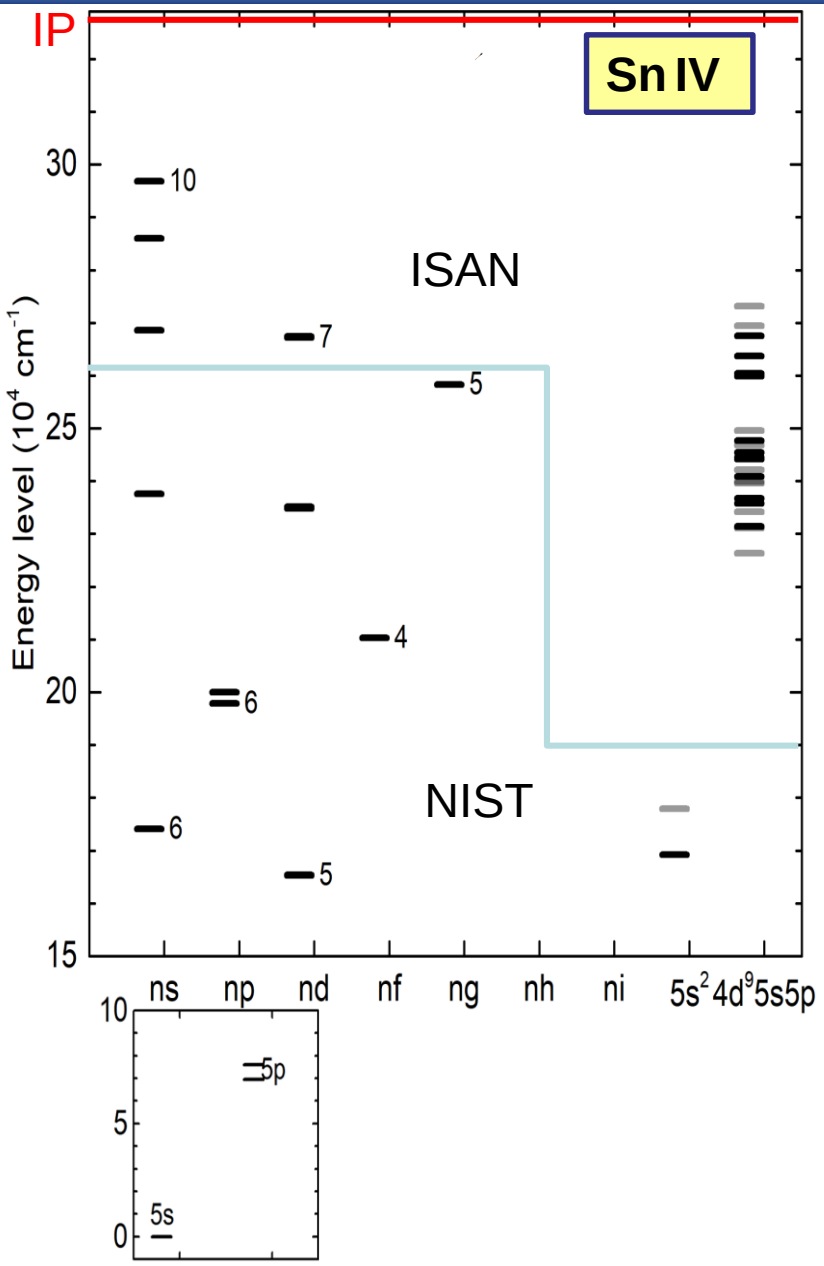
Sn^{3+} [Ag like]
quasi-one-electron system
$[Kr]4d^{10}5s$

most simple tin ion
one electron outside a closed $4d^{10}$ shell

existing information:
NIST database: Moore 1958
ISAN EUV spectroscopy: Ryabtsev *et al*, 2006

4f ^{2}F term most studied by theory
inverted, narrow fine structure
AgI, CdII, InIII, SnIV,
SbV, TeVI, IVII, XeVIII .....
[ground levels: $j = l + \frac{1}{2}$ and $j = l - \frac{1}{2}$]

of the **47** SnIV lines observed only **20** can be linked to the known levels



Level identification

level predictions:

- COWAN code (Ryabtsev)
- CoupledCluster (Borschevsky)

“issue”: High-resolution in the optical

uncertainty	ΔE cm^{-1}	$\Delta\lambda$ nm
0.1%	~250	~5

Quantum defect method (Edlen (1964)):
binding energy w.r.t. ionization level

$$E_{nl} = -R\frac{Z^2}{(n^*)^2} = -R\frac{Z^2}{(n-\delta_l)^2}$$

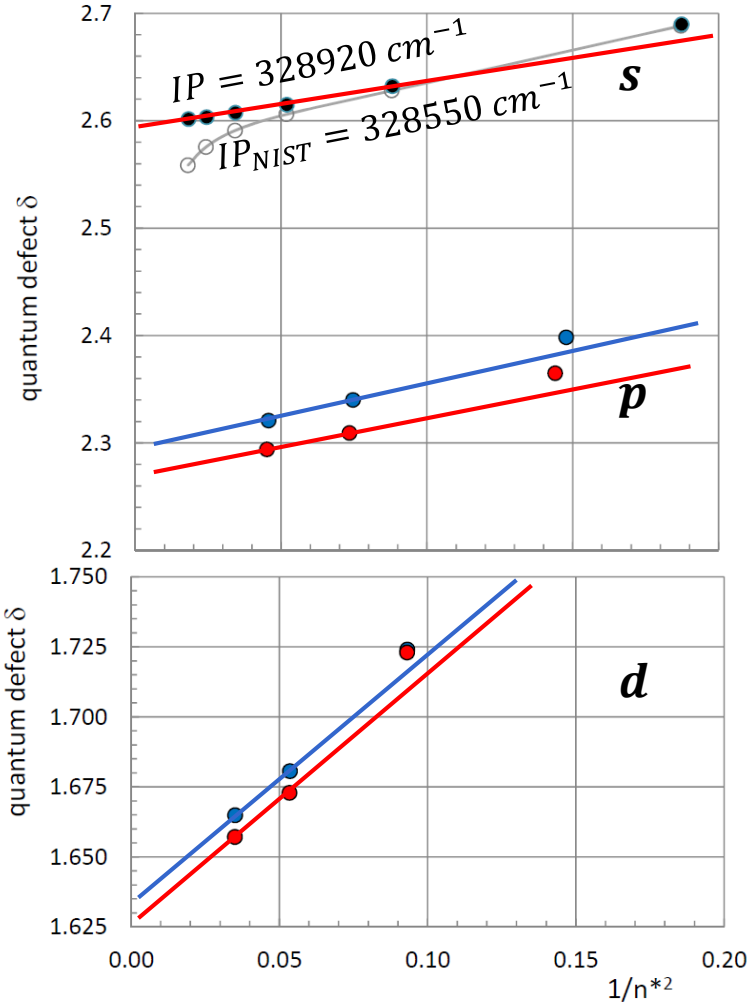
Taylor expansion:

$$\delta_l = a\left(\frac{1}{(n^*)^2}\right) + b\left(\frac{1}{(n^*)^2}\right)^2 + \cdots.$$

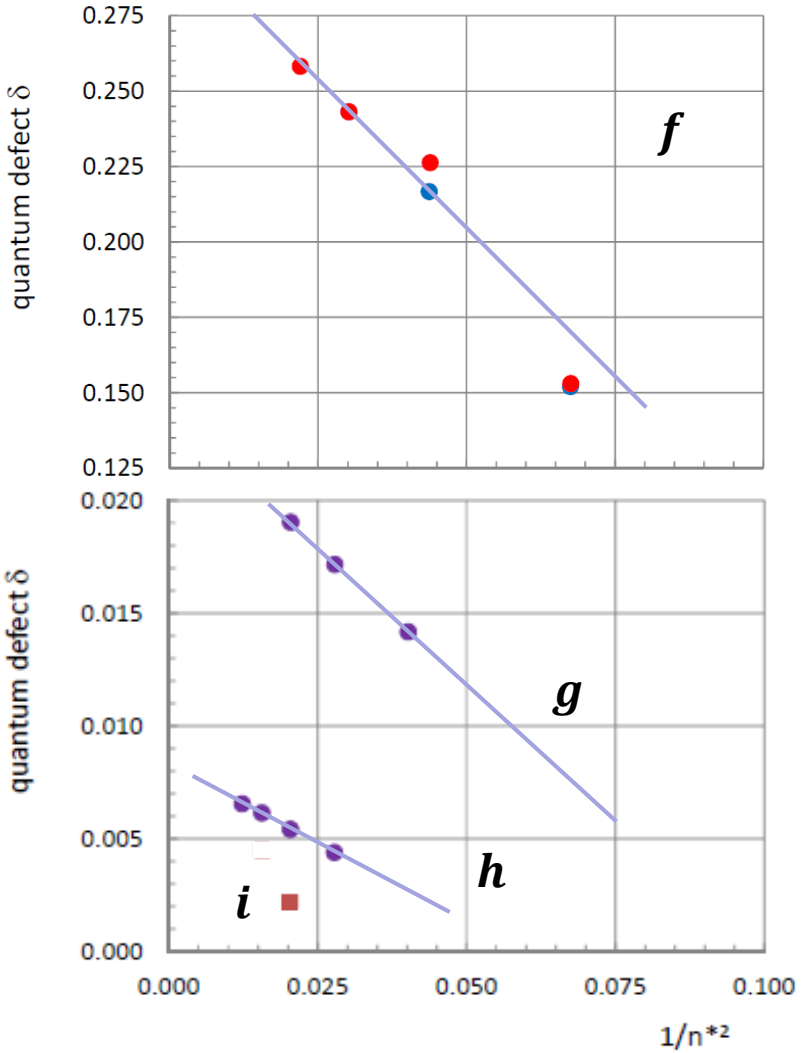
quantum defect scaling

Sn^{3+}: [Kr]$4d^{10}nl$ core is d^{10} $l_{core} = "d"$

$l \leq l_{core}$



$l > l_{core}$



anomalous results: 5d ^{2}D

Fine structure

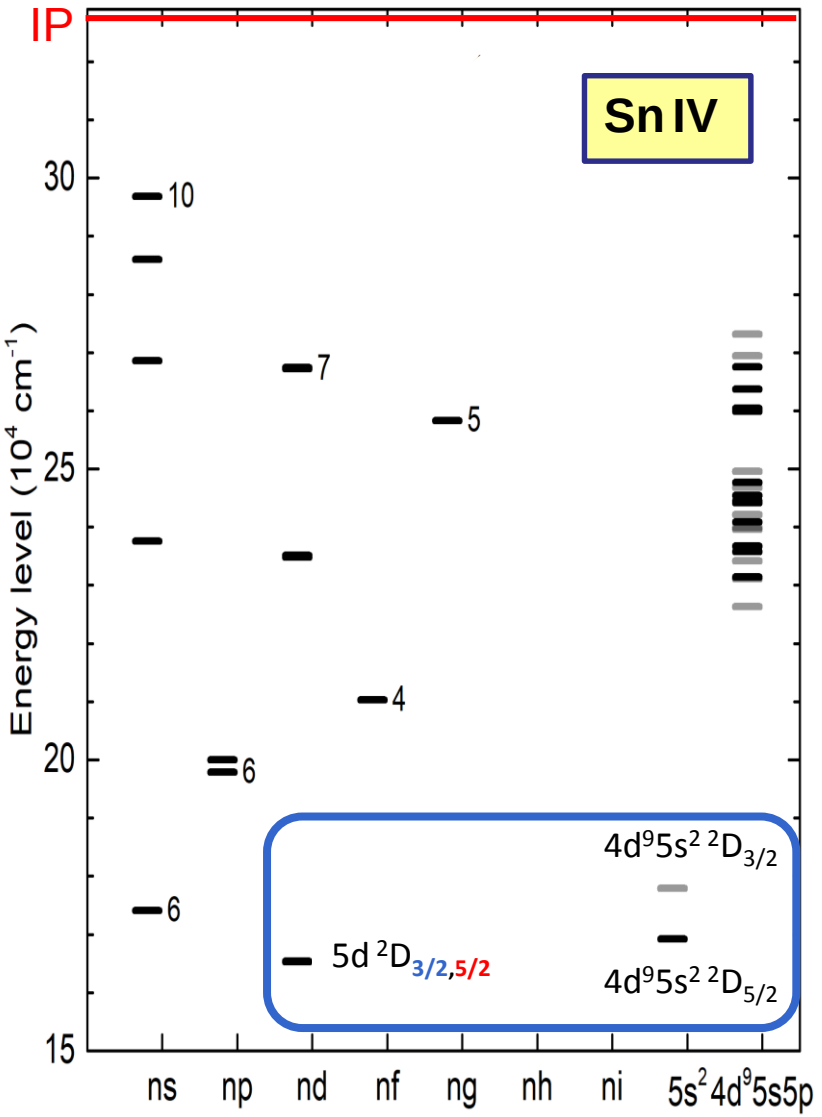
^2D_J — $J = \frac{5}{2}$

— $J = \frac{3}{2}$

5d ^2D_J fine structure	ΔE_{FS} [cm^{-1}]
NIST database	106
RMBPT*	745
this work	
Experiment	105
FSCC	735
FSCC - CI	120

* RMBPT: Safronova *et al,* PRA **68**, 062505 (2003)

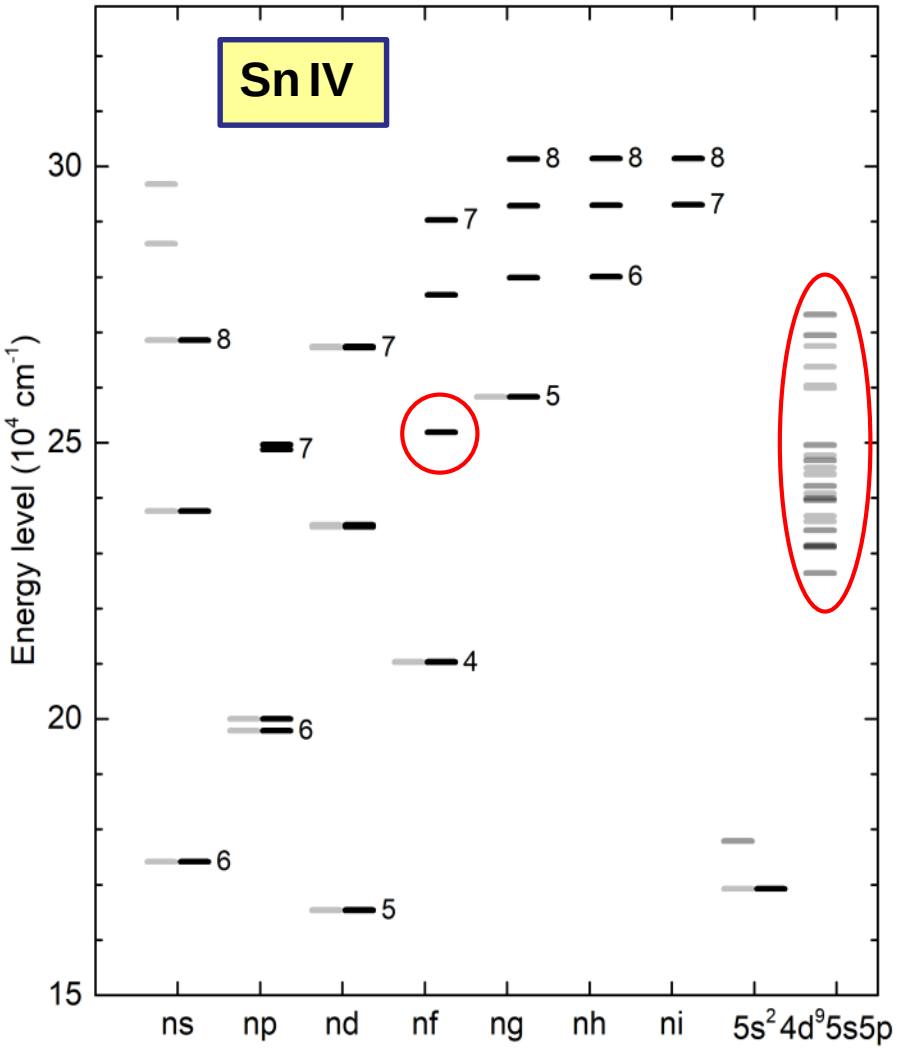
mainly shift of 5d $^2D_{5/2}$ due to configuration interaction with $4d^9 5s^2\ ^2D_{5/2}$ ~600 cm^{-1}



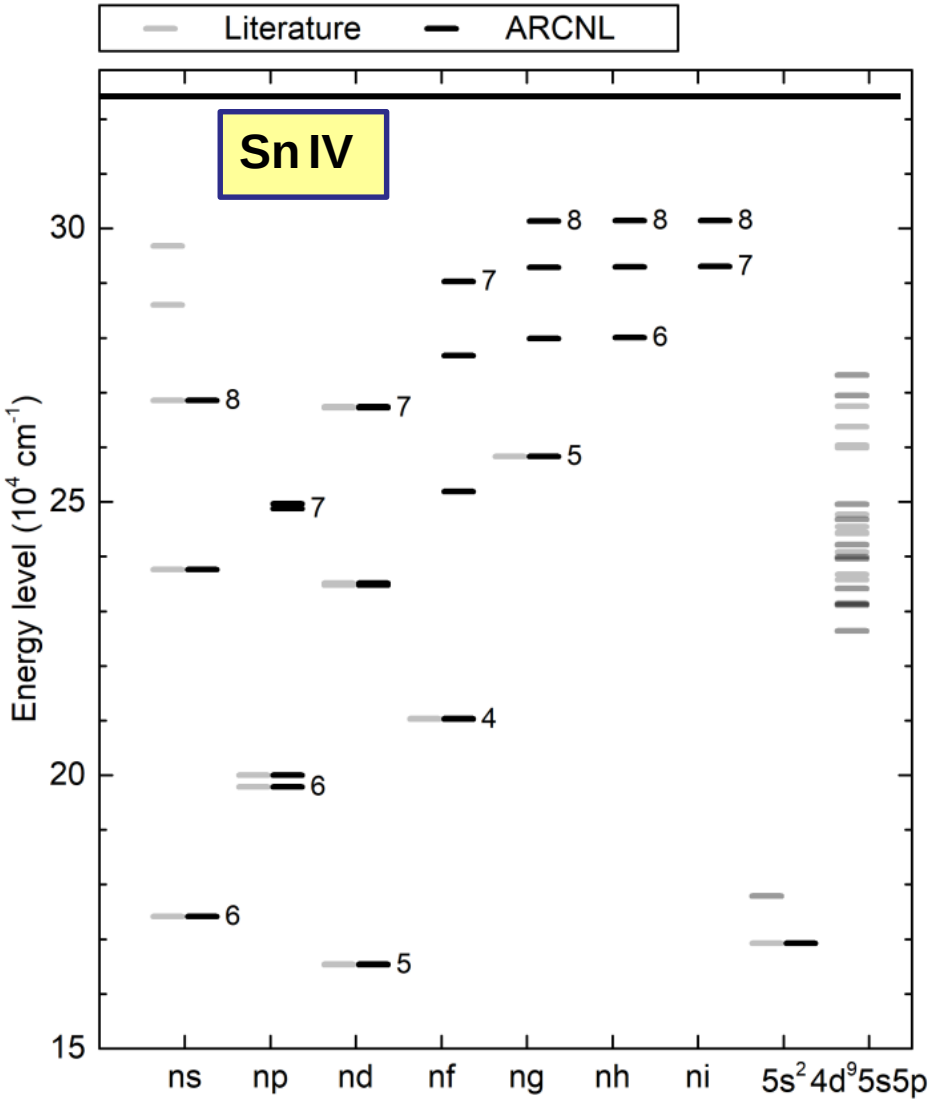
the inverted fine structure of nf ^{2}F

4f ^2F_J	ΔE_{FS} [cm^{-1}]
NIST database	-61
RMBPT*	-74
RPTMP#	-60
MCDHF$	-71
this work	
experiment	-60
FSCC	-62
MBPT	-62
5f ^2F_J	ΔE_{FS} [cm^{-1}]
RMBPT*	-44
RPTMP#	-22
this work	
experiment	-308
FSCC	-39
MBPT+CI	-43 / -572

*RMBPT: Safronova *et al,* PRA **68**, 062505 (2003)
RPTMP: Ivanova, ANDT, **97**, 1 (2011)
$MCDHF: Grumer *et al*, PRA **89**, 062511 (2014)



The Sn IV grotrian diagram



- IP = 328920 cm^{-1}
- 12 new terms
- anomalous fine structure 5d and 5f configuration interaction with hole states

conclusion

Overview “ARCNL” tin ion spectroscopy program

“ARCNL” = ARCNL + external collaborators

experiments outside arcnl:

- EBIT-based optical spectroscopy (Sn^{7+-15+})
  - [TALK: Hendrik Bekker]
- synchrotron/storage ring/crossed beam options explored

experiments at arcnl:

- LPP-based out-of-band EUV spectroscopy (Sn^{7+-15+})
  - [TALK: Francesco Torretti]
- LPP-based optical spectroscopy on lowly charged tin ions:
  - charge-state selective line identification
  - Sn IV: doubled the number of identified energy terms
    - ionization potential significantly corrected
    - anomalous structure effects identified and linked to configuration interactions